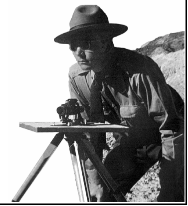
GEOLOGIC MONITORING PARAMETERS

Slope Failure (landslides)



Brief Description: There are many ways in which slopes may fail, depending on the angle of slope, the water content, the type of earth material involved, and local environmental factors such as ground temperature. Mass movements (landslides, mass wasting) may take place suddenly and catastrophically, resulting in debris and snow avalanches, lahars, rock falls and slides, flows (debris, quick clay, loess, and dry or wet sand and silt). For example, the initial velocity of mudflows can reach 30m/second in a few seconds, slowing to several m/day. Slower movements result in slides (debris, rock blocks), topples, slumps (rock, earth), complex landslides and creep. Landsliding is commonly regarded as one of the most predictable of geological hazards. Three parameters are particularly important for monitoring all kinds of mass movements.

1. Ground cracks are the surface manifestation of a variety of mass movements. In plan, they are commonly concentric or parallel, and have widths of a few centimeters and lengths of several meters, which distinguishes them from the much shorter desiccation cracks [see desert surface crusts and fissures]. The formation of cracks and any increase in their rate of widening is a common measure of impending slope failure.
2. The appearance of and increases in ground subsidence or upheaval is also a good measure of impending failure.
3. The area of slope failure is a measure of the extent of landsliding in any region. Changes over time may both reflect significant environmental stresses (e.g. deforestation, weather extremes) and provide important clues about landscape and ecosystem degradation.

Special conditions and processes exist in permafrost terrains. Landslides and mudflows of permafrost regions are mobilized and shaped by the freezing and thawing of pore water in the active layer, the base of which acts as a shear discontinuity. Failure here can occur on slopes as low as 1o. Gelifluction (a form of solifluction, the slow downslope movement of waterlogged soil and surficial debris) is the regular downslope flow or creep of seasonally frozen and thawed soils. Gentle to medium slopes with blankets of loose rock fragments overlying frozen ground may be subject to mass movements such as rock glaciers and rock streams or kurums [see frozen ground activity]. Catastrophic slope failure here can expose new frozen ground, setting off renewed mass wasting.

Climate change may accelerate or slow the natural rate of slope failure, through changes in precipitation or in the vegetation cover that binds loose slope materials: wildfires can also promote mass movements by destroying tree cover. However, it is difficult to generalize where information is lacking on the present distribution and significance of landslides, and because many parameters, in addition to climate change, contribute to slope stability.

Significance: Thousands of people are killed each year by landslides: in China and Peru, tens of thousands of deaths have resulted from single landslides. Annual property damage from landslides worldwide is estimated in the tens of billions of dollars, with more than $1.5 billion in annual losses in the USA alone. There are innumerable small to medium-size slope failures that cumulatively impose costs to society as great or greater than the large infrequent catastrophic landslides that draw so much attention. Damage to ecosystems has not generally been documented, but landslides may destroy habitats, for example by blocking streams and denuding slopes.

Environment where Applicable: Landslides are most common on moderate to steep slopes worldwide, but even gentle and flat-lying slopes may fail where adjacent to steep slopes, rivers, and other bodies of water. The risk of failure is generally greater where rocks are highly fractured, or where there are surficial soils, clays and silts that are liable to liquefaction. Many pre-existing landslides are re-activated, even under conditions that the original slope, prior to first failure, could have resisted.

Types of Monitoring Sites: The highest part (crown) of landslides and other potential failures is generally the most important place for monitoring cracks, subsidence and sagging. Upheaval or buckling generally begins in the toe area. As failure progresses and the slide or flow develops, cracks and ground subsidence may form at any point including the toe: one landslide in Japan formed cracks and uplifted a railroad tunnel in the toe area over 1 km away and on the other side of a river from the crown.

Method of Measurement: Surface methods for measuring the development of cracks, subsidence and uplift include repeated conventional surveying, installation of various instruments to measure movements directly, and tiltmeters to records changes in slope inclination near cracks and areas of greatest vertical movements. Subsurface methods include installation of inclinometers and rock noise instruments to record movements near cracks and other areas of ground deformation, bucket auger holes large enough to accommodate a person who locates, records and monitors cracking and deformation at depth, and geophysical techniques for locating shear surfaces throughout the landslide area. The areal extent of landsliding over large areas is most effectively determined using air photos. Satellite images may be helpful in identifying large landslides and in noting changes in soil and vegetation cover that may be associated with landsliding. Conversion of landslide extent from photos to a digital database will permit easy measurement of areal changes for each type of landslide deposit. At higher latitudes, color infrared photos at scales of 1:25,000 to 1:50,000 are best for most landslides, if taken in early spring or late fall (no snow or deciduous leaves) when sun angle is high and shadows are at minimum.

Frequency of Measurement: The frequency of monitoring will largely be dictated by changes in rate of crack propagation and ground deformation and by the degree of potential damage if the slope fails. For example, urban or industrial areas of high risk and rapid change will require continuous monitoring and, probably, the installation of automatic warning devices such as sirens and barriers. Areas of low risk and very slow development of cracks and ground deformation can be examined much less frequently. Critical periods for monitoring are during and immediately after intense rains and rapid snowmelt: real-time monitoring of rainfall from telemetered rain gauges and precipitation forecasts may be very important. Once a comprehensive and reliable baseline of past and present landslide activity has been established, the measurement should be repeated after hurricanes and other significant snowfall/snowmelt and rainfall events, or after fires, deforestation or human activities that extensively modify the land surface. If little activity has taken place in a particular area, re-assessment can be delayed for several years or more.

Limitations of Data and Monitoring: The factors influencing slope stability are numerous and often complex, and monitoring of cracks may provide little insight in dealing with particular landslides. Many cracks form and are followed by landsliding within seconds, as do many areas with active subsidence and upheaval, so that monitoring these slopes will not help in warning local residents. Other landslides may form cracks, subside or buckle over long periods of time and then fail suddenly with little warning. Other methods may be more useful for predicting failure, such as regional landslide hazard mapping, rainfall monitoring, and monitoring of pore water pressure. In assessing changes in areal extent, the skill of the interpreter, the quality of the air photography, and factors such as cloud and vegetation cover, haze, and sun angle may greatly limit the usefulness of the data. Many landslides cannot be detected on available air photos, and if their scale is too large, the expense and time required to analyze them may be prohibitive. Radar images may be needed for tropical area where vegetation cover is extensive. Most of the features used to identify landslides are too small be to recognized on currently available satellite images.

Possible Thresholds: Slope failure takes place when the critical slope angle is exceeded. The angle depends on the frictional properties of the slope material and increases slightly with the size and angularity of the fragments. Dry, cohesionless material will come to rest on similar material when the angle of repose ranges generally between 33o and 37o. For wet, cohesive materials underlain by frozen ground, downslope movement may occur on slopes as low as 1o. A related threshold for permafrost is the freeze-thaw transition [see frozen ground activity]. In humid areas of unstable slopes, the cumulative and anticipated rainfall may reach empirical threshold values, at which time warnings of impending slope failure should be issued.

Key References:

Berger, A.R. & W.J.Iams (eds). Geoindicators: Assessing rapid environmental changes in earth systems. Rotterdam: A.A. Balkema (see papers by Nesje, Rasch et al., Romanovskii et al.).

Brabb, E.E. 1984. Innovative approaches to landslide hazard and risk mapping. Proceedings of IV International Symposium on Landslides 1: 307-324.

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Casale, R., R.Fantechi & J.C.Flageollet 1995. Temporal occurrence and forecasting of landslides in the European Community. European Commission, 2 vols.

Jones, D.K.C. & E.M.Lee 1994. Landsliding in Great Britain. London: HM Stationery Office

Novosad, S. & P.Wagner (eds) 1993. Landslides. Proceedings of 7th International Conference on Landslides. Rotterdam:Balkema. (especially papers by Glawe et al. and Moriwaki).

Keefer, D.K. 1987. Real-time landslide warning during heavy rainfall. Science, 238: 921-925.

Selby, M.J. 1993. Hillslope materials and processes. 2nd edition. Oxford: Oxford University Press.

Schuster, R.L. & R.J.Krizek (eds) 1978. Landslides, analysis and control. U.S. National Academy of Sciences Transportation Research Board Special Report 176. (especially papers by Varnes, and Wilson & Mikkelson - N.B. A new edition is in preparation).

Related Environmental and Geological Issues: Removal of forest and plant cover (fire, deforestation); land clearing and accelerated soil erosion in sloping terrain; potential destruction of ecosystems affected by slope failure.

Overall Assessment: Slope failure is one of the most widespread causes of land disturbance, so that the initiation and development of landslides should be closely monitored.

Source: This summary of monitoring parameters has been adapted from the Geoindicator Checklist developed by the International Union of Geological Sciences through its Commission on Geological Sciences for Environmental Planning. Geoindicators include 27 earth system processes and phenomena that are liable to change in less than a century in magnitude, direction, or rate to an extent that may be significant for environmental sustainability and ecological health. Geoindicators were developed as tools to assist in integrated assessments of natural environments and ecosystems, as well as for state-of-the-environment reporting. Some general references useful for many geoindicators are listed here:

Berger, A.R. & W.J.Iams (eds.) 1996. Geoindicators: assessing rapid environmental change in earth systems. Rotterdam: Balkema. The scientific and policy background to geoindicators, including the first formal publication of the geoindicator checklist.

Goudie, A. 1990. Geomorphological techniques. Second Edition. London: Allen & Unwin. A comprehensive review of techniques that have been employed in studies of drainage basins, rivers, hillslopes, glaciers and other landforms.

Gregory, K.J. & D.E.Walling (eds) 1987. Human activity and environmental processes. New York: John Wiley. Precipitation; hydrological, coastal and ocean processes; lacustrine systems; slopes and weathering; river channels; permafrost; land subsidence; soil profiles, erosion and conservation; impacts on vegetation and animals; desertification.

Nuhfer, E.B., R.J.Proctor & P.H.Moser 1993. The citizens' guide to geologic hazards. American Institute for Professional Geologists (7828 Vance Drive, Ste 103, Arvada CO 80003, USA). A very useful summary of a wide range of natural hazards.